

Universal Dynamics in Flow-Induced Cable Vibration

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LONG-TERM GOALS

The long-term goal is to use tools from study of nonlinear chaotic dynamics to better understand fluid-structure interaction problems in vibrating cables and bluff bodies. The overall objective is to organize results on vibrating cables into a dynamical systems-based framework. A second goal is to advance current fluid-structural modeling through combined analytical-experimental work.

OBJECTIVES

The expected outcomes of the study will be; 1) advances in state-of-the-art fluid-structural modeling through supporting experimental work, 2) new techniques for flow control in oscillating bluff body flows, and 3) development of new analytical techniques to better predict vibrating cylinder wakes using certain aspects of spatial-temporal chaos theory.

APPROACH

A combined analytical-experimental approach is used. Analytical aspects focus on the continued development of a low-order model that utilizes a series of diffusively coupled circle map oscillators along the cylinder span. This coupled map lattice has been extended to include control logic to develop a very efficient low order model for control studies in cylinder wake flows. On the experimental side our recent focus has been on development of a novel, non-intrusive circulation measurement technique which yields spatial lift distributions along the span of an oscillating bluff body.

WORK COMPLETED

One of the proposed objectives of this grant was the experimental measurement of spatial lift distributions along the span of an oscillating bluff body. In response to this we have developed an ultrasonic circulation (lift) measurement technique. This method (detailed in Figure 1) uses sound propagation along an acoustic path enclosing the bluff body. The fluid circulation on the closed path is proportional to the difference in transit times of oppositely directed acoustic pulses along the acoustic path. The measured circulation is proportional to the lift force through the Kutta-Joukowski theorem under appropriate conditions. The acoustic path can be moved to any location along the bluff body span to measure the spatial lift distribution. Smoke-based flow visualization techniques have also been developed to visualize near-wake vortex structures along the bluff body span. Our goal is to correlate

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measured local lift forces along the bluff body span with observed wake structures, and to analyze the resulting lift force dynamics using dynamical system based tools.

Flat plate bluff bodies are currently being studied, as they possess certain advantages over circular cylinders. Flat plate bluff bodies generate a mean lift (our initial experimental capability), and allow for study of streamlined, stalled, and bluff body flows respectively through simple variation of angle of attack. Sampling rate limitations (imposed by acoustic path length) in the instantaneous circulation measurement technique would restrict us to large diameter (i.e., rigid) cylinders. However, a flat plate of equivalent chord length remains a flexible structure (vibrating ribbon, for example).

We have continued to develop our low-order model (coupled map lattice) to include flow control logic with the goal of developing an efficient model for flow control studies in cylinder wakes. The coupled map lattice;

$$\theta_{n+1}^k = (1 - 2\varepsilon)f^k + \varepsilon(f^{k+1} + f^{k-1})$$

$$f^k = \theta_n^k + \Omega^k - \frac{K^k + C_n^k}{2\pi} \sin[2\pi\theta_n^k - \phi^k - \frac{\pi}{2}],$$

now includes flow control logic through the C_n^k control term added to the nonlinear K^k term. In the past chaos control logic was incorporated into the model. This year more sophisticated control logic has been added to the model. These discontinuous nonlinear control techniques are based on feedback linearization of a nonlinear control signal.

RESULTS

A typical mean lift distribution (measured with the ultrasonic technique) on a stationary flat plate bluff body with a sinusoidal variation in plate chord length (to impose wake three-dimensionality along the span) is shown in Figure 2. The three-dimensional lift distribution varies significantly from the nominal 2-D distribution based on local chord length. We are currently working to correlate near-wake vortex size (from our flow visualization results) with the measured lift distributions.

While our present work has focused on stationary, three-dimensional bluff bodies in proof-of-concept studies of this technique, we plan to study oscillating bluff bodies in the near future. We are also currently extending the ultrasonic technique to measure instantaneous, unsteady lift forces (at any spanwise location) during an entire vortex shedding cycle. Our goal is measurement of instantaneous, local lift measurements along the span on a flexible, freely vibrating flat plate (ribbon) in a standing wave mode. Rigid, oscillating cylinders with spanwise diameter variation (following Nuzzi et al. 1992) will also be studied. These instantaneous lift forces would then be analyzed using our dynamical systems tools and framework.

We have shown that the new nonlinear control techniques incorporated into the coupled map lattice stabilize periodic states (parallel shedding) more efficiently than the previous chaos control techniques (see Figure 3). This improvement in efficiency can be explained using a dynamical systems perspective (Figures 3c, d). Both control techniques successfully drive the system into the lock-on region to stabilize periodic states, however the nonlinear control methods (Fig. 3d) minimize the

required control input to achieve this condition when compared to the chaos control logic. The studies also provide spanwise forcing distributions ($K^k + C_n^k$) which can be implemented in experimental studies on the same flows to determine if parallel shedding results.

IMPACT/APPLICATIONS

The developed ultrasonic circulation technique could ultimately allow for non-intrusive lift measurements along oscillating bluff body (cable) structures in marine environments. The coupled map lattice provides a very efficient low-order model for flow-structure interaction in cylinder wakes. Computational times on the order of 1000 shedding cycles per CPU second are attainable. Low-order models such as this are actively sought by researchers in the field. The low-order flow control model can be used for efficient feasibility studies on control techniques in wake flows, prior to more extensive experimental studies. The nonlinear, discontinuous and chaos control techniques could also provide straightforward experimental control schemes for stabilizing complex flows.

RELATED PROJECTS

We have interacted with Prof. Karniadakis's group at Brown University to establish connections between their numerical formulations and our low-order coupled map lattice. Side-by-side comparisons of wake structures predicted by the two methods have appeared in journal publications (Olinger, 1998). In the future we hope to extend this interaction to further quantitative comparisons of coupled map lattice and numerical simulation results. We also plan to compare our experimental lift distributions to numerical results.

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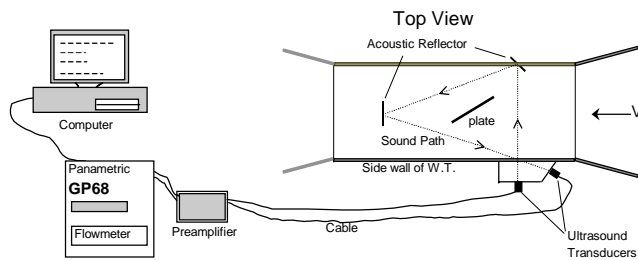


Fig 1(a) Schematic of the ultrasonic circulation measurement technique

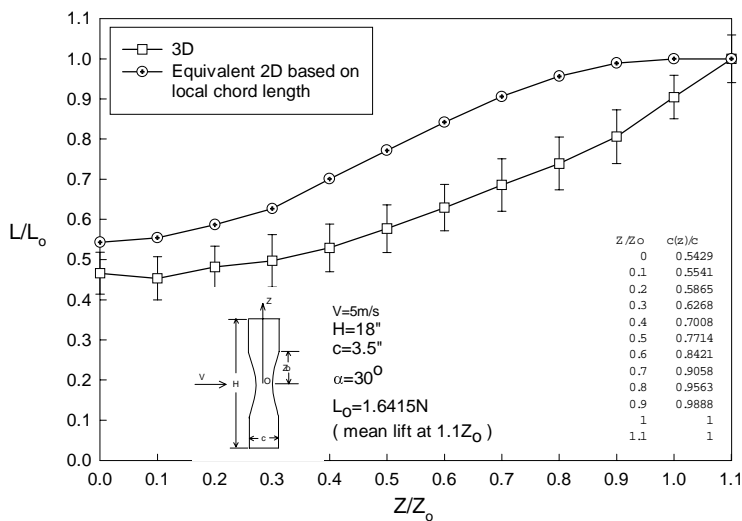


Fig. 2(a) Mean lift spanwise distribution of a plate with sinusoidal leading and trailing edges

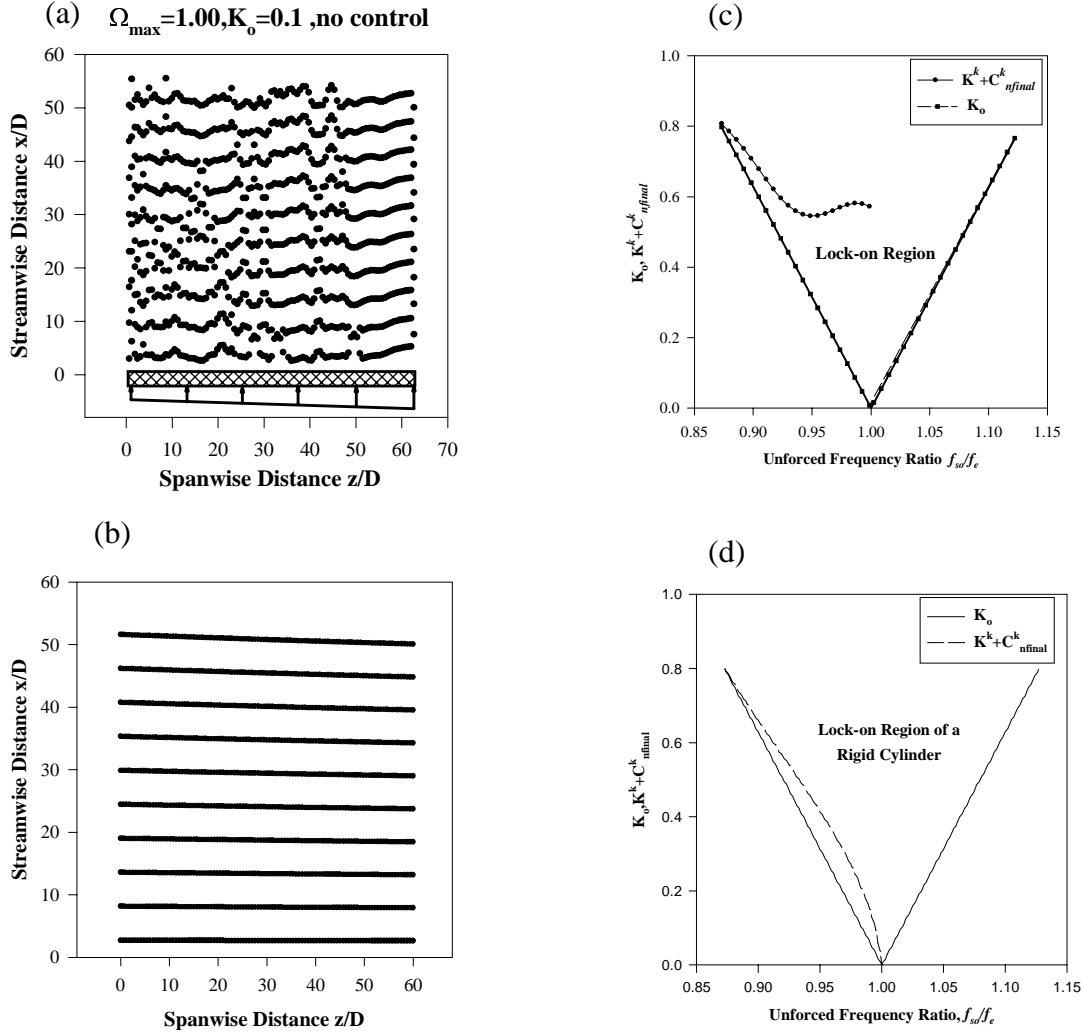


Figure 3. Results from low-order flow control model.

- a) Uncontrolled case - complex wake structure resulting from freestream shear flow.*
- b) Periodic, parallel shedding after application of discontinuous, nonlinear control technique.*
- c) Frequency-amplitude plane for chaos control case showing system is driven into circle map lock-on region.*
- d) Frequency-amplitude plane for nonlinear control case showing efficiency of method compared to chaos control.*